Lock-in amplifier 2306 is of the type that is sensitive to one or more particular frequencies. The frequency or frequency range to which the lock-in amplifier is sensitive may be pre-determined or the RF source 2302 may optionally be fed back to the lock-in amplifier. The RF source may optionally be fed back to the lock-in amplifier via optional delay line 2308. Optional delay line 2308 may optionally be a variable delay line controlled by controller 118. Lock-in amplifier 2306 may be of a design that locks into the frequency of the illuminator pulse modulation and follows it through any variation. One type of such design is a phase-locked loop, which may be implemented as a heterodyne design, for example.

Optional modulator 2304 may apply modulation to the RF signal generated by RF source 2302, thus driving illuminator 104 with a modulated RF signal. Some or all of RF source 2301, optional modulator 2304, illuminator 104, scanner 108, detector 116, lock-in amplifier 2306, optional delay line 2308, and optional interface 120 may be under control of controller 118, for example via control lines 2202.

The RF drive signal produced by timer-controller 2301 effectively produces a carrier frequency that tunes illuminator 104 and synchronous detector 2305 to each other and helps to reject ambient noise and provide other benefits, some of which are described herein.

Scanned beam imagers often have data rates on the order of 20 MHz. One way to operate a synchronous detector with a scanned beam imager is to pulse the beam at a frequency that is high compared to the data rate. For instance, the beam may be modulated at a rate of 20 to 200 times the data rate, resulting in a pulse rate of 400 MHz to 4 GHz. Such high pulse rates can be a challenge for detectors, however, often resulting in significant photon shot noise as well as practical design difficulties. In a preferred embodiment, the pulse rate may be run at a small multiple of data rate, for example at 1 to 10 times the data rate, resulting in a more manageable pulse rate of 20 to 200 MHz.

The device of Figure 23 may operate at a pre-determined pulse frequency. It may desirable, particularly in low frequency multiple embodiments, to maintain a constant phase relationship between pixel clocking and synchronous pulse modulation in order to ensure an equal number of pulse modulation cycles. However, preferred resonant scanning technologies do not have constant rotational velocities.

For resonant scanning systems, constant frequency pulse modulation may be used with constant pixel clock rate and variable pixel spacing. In this mode, it may be desirable to apply image processing to interpolate between actual sample locations to produce a constant pitch output. In this case, the addressability limit is set at the highest velocity point in the scan as the beam crosses the center of the FOV. More peripheral areas at each end of the scan where the scan beam is moving slower are over-sampled. In general, linear interpolation, applied two-dimensionally where appropriate, has been found to yield good image quality and have a relatively modest processing requirement.

Alternatively, constant pixel spacing may be maintained by varying both pixel clocking and synchronous pulse modulation frequency. Methods and apparatus for varying pixel clocking across a FOV are described in U.S. Patent Application 10/118,861 entitled ELECTRONICALLY SCANNED BEAM DISPLAY by Gregory Scott Bright, Scott W. Straka, Philip C. Black, James G. Moore, John R. Lewis, Hakan Urey, and Clarence T. Tegreene, filed 4/9/02, commonly assigned and hereby incorporated by reference.

By using a clock divider (for frequency ratios greater than 1:1) or a second clock, one may use the apparatus disclosed therein to also control pulse modulation frequency synchronously with pixel clocking.

Varying the pulse modulation frequency sinusoidally produces a chirp that may be useful for further improving noise immunity. In effect, this creates frequency diversification that acts in a manner similar to spread spectrum radio

systems. This may be particularly useful when two or more of the systems of Figure 23 are used in proximity to one another.

Pulse modulation frequency diversification may also or alternatively be implemented by varying the ratio of modulation frequency to pixel frequency. This may be done on a frame-by-frame, line-by-line, or even a pixel-by-pixel basis. This type of modulation frequency diversification is particularly akin to frequency hopping spread spectrum radio systems. A programmable clock divider may be used to set the frequency ratio.

Figure 24 is a diagram showing exemplary waveforms for a synchronous illuminator and detector. Note that for clarity, scale designators and correspondence to particular shades of gray have been changed from the non-synchronous case presented in Figure 6a. Idealized scanned detection spot or pixel 2401 is shown at various positions along scan path 112 in FOV 111. Thus, scan path 112 may be thought of as representing both a spatial axis and a time axis. For purposes of clarity, various complications including elongation in the scanning direction are omitted. FOV 111 is shown having, right-to-left, a medium gray region 606, a light region 602, a dark gray region 608, and a light region 602. Waveforms 2402 through 2412 are shown aligned below corresponding detection spot locations/times.

Waveform 2402 represents an initial synchronous illumination waveform. It can be seen that the illuminator power is chopped twice per pixel position. Thus Figure 24 represents a case where synchronous chopping is performed at a frequency equal to twice the pixel frequency.

Waveform 2404 represents an initial (pre-converged) detector response. It can be seen that medium gray region 606 returns a detector signal that falls within the dynamic range of the detector. Light regions 602 return an indeterminate (high) signal designated ≥10. Dark gray region 608 returns an indeterminate (low) signal designated 00. Thus, only the medium gray region 606 returns a signal that falls within the dynamic range of the detector.

Waveform 2406 illustrates a converged synchronous illuminator waveform and waveform 2408 the corresponding converged (determinate) detector waveform. In this case illuminating medium gray area 606 with an illuminator power of 10, illuminating light areas 602 with a power of 01, and illuminating dark gray region 608 with a power of 11 results in a determinate detector response of 01. The alternating 00 levels in both waveforms represent the synchronous chopping of this embodiment. This embodiment corresponds to an amplitude modulated (AM) encodation.

Waveform 2410 represents an alternative method of modulating illuminator power in a synchronous system. In this case, medium gray region 606 receives "on" pulses of medium width, light regions 602 receive "on" pulses of narrow width, and dark gray region 608 receive "on" pulses of wide width. As shown, the leading edges of the illuminator "on" pulses are maintained at a constant frequency. Alternatively, the trailing edges could be maintained at a constant frequency with the leading edges being advanced or retarded in a manner inversely proportional to the apparent brightness of the pixel, or the mid-points could be maintained at a constant frequency with both the leading edges and trailing edges extending farther or nearer to the midpoints in a manner inversely proportional to the apparent brightness of the pixel, respectively. Waveform 2410 corresponds to pulse width modulated (PWM) encodation.

Waveform 2412 illustrates another alternative method of modulating illuminator power in a synchronous system. In this case, the phase of the illumination pulse 2412 is varied to produce greater or lesser coupling with the detector waveform 2408. Thus, medium gray areas 606 receive a slight phase offset, here shown as a phase delay. Similarly, light areas 602 receive a large phase offset and dark gray area 608 receives no phase offset. Accordingly, the detector "sees" a relatively powerful returned signal from light areas 602 for a short time, a medium signal from medium areas 606 for a medium time, and a relatively weak signal from dark gray region 608 for a relatively long time. This

control schema corresponds to phase shift keyed (PSK) encodation. Apparent brightness encodation methods other than AM, PWM, or PSK may additionally be used.

The synchronous detection schema presented in Figure 24 may additionally be used in embodiments where the illuminator power or coupling is not modulated. For these cases waveform 2402 represents illuminator output and waveform 2414 represents detector response. Medium gray region 606 returns to the detector a medium power signal corresponding to level 10. Similarly, light regions 602 return high power 11 signals and dark gray region 608 returns a low power 01 signal. AM, PWM, PSK, or other modulation may be used on detector sensitivity or gain by methods analogous to those used in the illuminator encoding systems described above.

The use of synchronous illuminator(s) and detector(s) creates a "carrier frequency" that is beneficial for improving system performance with respect to range, noise and ambient light immunity, cross-talk reduction, reduction in illuminator power requirements, reduction in detector bandwidth requirements, and other benefits.

While the ratio of pulse modulation frequency to pixel frequency shown in Figure 24 is 2:1, other multiples may alternatively be used. Moreover, integer ratios are not necessarily required, although integer ratios typically simplify design and calculation.

Referring back to Figure 23 with reference to Figure 24, the illuminator 104 may be AM modulated via control line 2202. Optionally, illuminator 104 may be PWM modulated via optional modulator 2304. PSK modulation may be embodied by a variable phase RF source 2302 or a programmable delay line (not shown) inserted between RF source 2302 and illuminator 104. An alternative way of PSK encodation is to use optional programmable delay line 2308 to modify the phase of detector sensitivity while leaving the illuminator pulse phase substantially constant. RF source 2302 may optionally be replaced by a clock divider or other

interface for driving sinusoidal or chirped synchronous pulse modulation from a variable pixel rate. A programmable clock divider can be used to implement a frequency ratio hopping system.

Figure 25 is a compact illuminator having three emitters. Emitters 1103a, 1103b, and 1103c, which may for instance be RGB lasers or edge-emitting LEDs are held by mounts 2502a, 2502b, and 2502c, respectively. Mounts 2502 may include provision for aligning the emitters. Light beams output by emitters 1103a, 1103b, and 1103c are combined by X-cube 2504 and output along a common axis as combined beam 106. X-cube 2504 may be a commercially available birefringent device. The output beam 106 proceeds down mounting barrel 2506 and is collimated or focused by output optic 1106, here shown as a doublet. Alternatively, output optic 1106 may be implemented as a single lens and or an aperture (not shown). Spacers 2508a and 2508b vary the optical path length between the three illuminators 1103a, 1103b, and 1103c and output optic 1106, thus compensating for chromatic aberration. The compact three color illuminator 104 or Figure 25 may be used in combination with scanned beam embodiments shown elsewhere in this document.

High speed MEMS mirrors and other resonant deflectors are often characterized by sinusoidal scan rates, compared to constant rotational velocity scanners such as rotating polygons. Resonant deflectors may be resonant in one, two, or three axes. In certain instances, the scan pattern follows a path characterized as a Lissajous pattern. In this case, the intersections between the vertical and horizontal lines of the rectilinear matrix represent idealized pixel positions while bi-resonant scan path represents the actual path taken by the scanned spot. The actual scan path doesn't align perfectly with all the rectilinear pixel positions. These values may therefore be determined by interpolating.

Methods for selecting bi-resonant frequencies as well as methods for maximizing the image quality are discussed analogously in the U.S. Patent Application entitled APPARATUS AND METHOD OF BI-DIRECTIONALLY

SWEEPING AN IMAGE BEAM IN THE VERTICAL DIMENSION AND RELATED APPARATI AND METHODS, by Margaret Brown, Marc Freeman, and John R. Lewis, application number 10/441,916, applied for May 19, 2003, commonly assigned herewith and hereby incorporated by reference.

The preceding overview of the invention, brief description of the drawings, and detailed description describe exemplary embodiments of the present invention in a manner intended to foster ease of understanding by the reader. Other structures, methods, and equivalents may be within the scope of the invention. As such, the scope of the invention described herein shall be limited only by the claims.